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QUALITY CONTROL AND NONDESTRUCTIVE EVALUATION
TECHNIQUES FOR COMPOSITES - PART VII:
THERMOGRAPHY - A STATE-OF-THE-ART REVIEW

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ABSTRACT

A review of techniques available for the application of thermo-
graphic nondestructive testing and evaluation techniques is presented.
General information on contact and noncontact methods of temperature
measurement are discussed as these pertain directly to thermography.
Special emphasis is placed on noncontact, infrared methods as these
can be used for real-time observations. Practical information on the
procedures which have proven useful for application of thermography
to composites is discussed in some detail. In addition, present
equipment which is available commercially for such tests and important
test parameters which must be selected for proper observations and
interpretations are discussed. Finally, a brief survey of the lit-
erature on the application of thermography to composites is given.

PREFACE

This project was accomplished as part of the U.S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Research and Development Command, ATTN: DRDAV-EGX, 4300 Goodfellow Blvd., St. Louis, MO 63120.

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Quality Control and Nondestructive Evaluation Techniques for Composites, Part VII: Thermography--State-of-the-Art Review

Background:

Thermography is the general term given to the technique whereby contours of equal temperature--isotherms--are mapped over a surface. As a technique for nondestructive testing and evaluation, the application of thermography is based upon the assumption that defects, inhomogeneities, or other undesirable conditions of the test object will evidence themselves as local hot or cold spots in the isothermal mapping. To apply this technique one must, first, excite a thermal pattern in the test object to be studied; second, measure the areal temperature distribution on the surface of the examined test object; and, third, interpret the results according to well-established and understood physical principles. This report on thermography will describe the present state-of-the-art for performing these steps for the study of composite materials. The state-of-the-art is well advanced for performing steps one and two but is still in the developmental stage for step three. While the physical principles of heat conduction and radiation are well understood, the interpretation of these principles for predicting type and effect of damage or defects needs further study.

For convenience, thermography NDT techniques may be categorized as active or passive (Ref. 1) when referring to the means by which heating is excited in the test object. Active methods refer to those for which heat is produced "actively" in the specimen by transformation processes which occur while the test object is being subjected to normal operating,

testing, or loading conditions. For example, an electrical component may overheat due to some abnormality when electrical current passes through it, or a structural material might develop hot spots under mechanical loading in regions where damage is occurring. On the other hand, passive methods refer to those for which the test object is treated as a path for heat from some external heat source to some external heat sink. In this case, local inhomogeneities or flaws will cause local differences in thermal conductivities which will evidence themselves in the thermal mapping. These categorizations will be dealt with in more detail in the section on the application to composites.

The means by which the temperatures are measured can also be conveniently categorized, in this case, as contact or noncontact methods (Ref. 2). Contact methods of temperature measurement very obviously refer to those by which a physical object is brought into contact with the surface of the test specimen to determine the temperature of the latter. Noncontact methods are those which rely upon infrared radiation to determine the temperature of the radiating source. Both types will be discussed in the next section on Thermographic NDT.

Temperature Measurement for Thermography

Contact Methods

As noted earlier, the second step in applying thermographic NDT is to measure the surface temperature of the object to be examined. (The first step, exciting the thermal pattern, will be discussed with application to composite materials in mind in the next section.) Perhaps the oldest and least expensive methods for doing this fall under the category

of contact methods. Such methods require that actual contact by made between the surface of the examined object and the measuring device. There are a large variety of possible techniques for making contact surface temperature measurements, most of which rely upon some type of chemical reaction in an applied coating. Thermal coatings include paints, phosphors, papers, liquid crystals, and a number of other, special temperature sensitive compounds. These methods have the distinct advantages of being relatively easy to apply and of requiring a low initial investment, particularly if only a small area of material is to be examined. On the other hand, these methods have the disadvantages of generally yielding only a qualitative indication of temperature and of affecting, themselves, the distribution of surface temperature. There are, however, some contact coatings such as liquid crystals, which can be calibrated for temperature measurement. A major disadvantage, common to all of the contact methods, is that one must know, a priori, the approximate value of the temperature that he wishes to measure.

To apply a contact thermographic method, a temperature-sensitive coating must be placed upon the surface of the examined test object. A change in temperature is evidenced by a change in color or appearance of the coating due to a temperature-sensitive chemical or physical change. This change may be either reversible or permanent, depending upon the type of coating used. As mentioned in the previous paragraph, there are several types of coatings that have been used for thermographic NDT. Additional details may be found in the survey presented in Ref. 2, but some of the highlights of their use are described in the subsequent paragraphs.

Temperature sensitive paints have been developed for use between 40° to 1600°C. These paints undergo a color change at a temperature which, under optimum conditions, can be calibrated to within ±5°C. Some paints exist which will progress through several different color transitions. Most often the color transitions are observable under ordinary light, but certain paints exist which may require the use of ultraviolet.

Another coating, which normally requires ultraviolet light for its use, is the thermal phosphor type. These phosphors, as with many such compounds, emit visible light when excited by ultraviolet radiation. For a thermal phosphor, the intensity of the emitted visible light varies inversely to its temperature. The rate of decrease of light intensity with temperature is very rapid at a critical temperature, as much as 25%/°C within a very limited temperature range around the critical point. Various phosphors exist for use between room temperature and 400°C. There are several ways in which a phosphor may be applied to a surface: as a paint, a stripable coating, in a tape, or as a powder.

At least three different types of thermally sensitive papers exist for thermographic NDT: organic, plastic and infrared copy papers. Organic papers are coated with a meltable organic substance. Upon reaching the melting temperature, the organic substance melts and is absorbed by the paper, turning its color from white to black. Plastic coating papers are constructed with a plastic coating containing a large density of air bubbles. These bubbles diffuse incident light giving the paper a pale color. Upon reaching the critical temperature of the paper, the plastic melts, releasing the bubbles and revealing the black

color of the paper underneath. The infrared copy papers contain dye precursors which react to produce a color when melted.

Reinitzer discovered liquid crystals in 1888, but they remained more or less unused until the 1950's. Liquid crystals refer to a special class of materials which at certain temperatures possess the properties of both a liquid and a crystal. These materials will flow as a viscous liquid while retaining the short range molecular structure of a crystalline solid. One form of liquid crystals, the so-called cholesteric, are dichroic. When unpolarized light is incident upon a dichroic material, it is decomposed into two components, one of which is circularly polarized clockwise while the other is circularly polarized counterclockwise. One of these components is transmitted and the other is reflected. The reflected component produces a color when the material is illuminated by white light. As cholesteric liquid crystals are heated, the distances between molecular layers increases. This distance governs the wavelength of the reflected light. Eventually the liquid crystal melts, and with further increase in temperature, becomes more and more disordered until eventually it achieves the state of an isotropic liquid. One can select liquid crystals from a wide variety of possibilities such that the liquid crystal appears colorless at low temperatures, changes through a succession of colors as it melts and approaches isotropy, and again becomes colorless when the material is totally isotropic. It is possible to obtain many different liquid crystal compounds which exhibit color changes at any temperature from -20° to 250°C. The various compounds have varying color-change temperature ranges from 10 to 30°C. The response time is relatively fast, 0.1 to

0.2 sec. The sensitivity for the detection of flaws by liquid crystals can be quite good. Depending upon the thermal conductivity and the proximity of the flaw to the surface, flaw sizes as small as 1/8" square have been detected.

Several other temperature-sensitive compounds have found some application in thermographic NDT. Thermochromic order-disorder compounds are one class of these. Thermochromic order-disorder compounds change color with temperature without breaking chemical bonds and hence are reusable. Variable surface-tension compounds have been developed with temperature-sensitive surface tension (Ref. 2). When sprayed upon a surface, these compounds are repelled from warmer areas and coalesce in the cool areas. Hence, these compounds are more sensitive to temperature differences than they are to the absolute value of the temperature. Finally, frost testing has been applied in situations where one wishes to find gross flaws or disbonds. To apply this method, one chills the surface of the examined object below the frost point so that a frosted surface is obtained. Differences in heat conductivities in the test object will then evidence themselves by the patterns formed as the frost melts.

Noncontact Methods

Noncontact methods for temperature measurement are based upon the phonomenon of infrared radiation. Sir Frederick W. Herschel discovered in 1800, in a very simple but elegant experiment, that there existed a portion of the electromagnetic spectrum, invisible to the human eye, with frequencies below that of the red portion of the visible spectrum (Fig. 1). This "infrared" light caused higher temperature

readings on thermometers than did visible light. Later workers found that, as a basic law of nature, all matter at temperatures greater than absolute zero spontaneously emits infrared, or thermal, radiation. Furthermore, the intensity and other properties of this radiation is predictable by a mathematical model, as described later. The radiation is a result of the thermal agitation, or temperature, of the basic components of which all matter is composed: molecules, atoms and sub-atomic particles. The frequency range covered by infrared radiation is a result of the various energies possessed by the wide range of molecules, atoms and sub-atomic particles and the various types of motions and quantum jumps available to these particles. Classically, the infrared spectrum was categorized into three subregions--near, intermediate, and far infrared, depending upon the value of the infrared frequency in relation to the red spectrum. The initial reason for this classification was due to the different experimental techniques required to detect the radiation in these different bands. However, in general, one can discuss these three bands in relation to the mass of the source of the infrared (Ref. 3): i) sub-atomic particles whose quantum jumps are responsible for the majority of near infrared, ii) atomic particles whose thermal vibrations produce the majority of intermediate infrared, and iii) molecules whose vibration and rotation motions produce the far infrared.

The basic properties of infrared radiation had been experimentally determined and were very well known, but no analytical model existed to account for them until Planck suggested his now quite famous model for black body radiation exactly one hundred years after infrared radiation

had been first discovered. Planck's major contribution to this field, and to modern physics in general, was his quantum hypothesis. Planck hypothesized that a harmonic oscillator, moving in one dimension, could not possess any value of energy in a continuum of energies, but could only have a total energy value which would satisfy the relationship

$$E = nh\nu \qquad\qquad [1]$$

where E is the total energy of the oscillator, ν is the frequency of oscillation, n is an integer, and h is a universal constant (Planck's constant, h = 6.625×10^{-34}Wsec^2.). Because of the discrete nature of energies available to a system of harmonic oscillators, such as the atoms or molecules composing a mass of matter, when one calculates the total energy contained therein, one must use an infinite discrete summation of energies rather than an integration over a continuous function. The difference in mathematical properties of a discrete summation in comparison with a continuous integration, led Planck to derive his well-known distribution law for spectral radiation emittance:

$$W_\lambda = 2\pi(10^{-9}) \frac{hc^2}{\lambda^5} \left[e^{\frac{hc}{\lambda kT}} -1 \right]^{-1} \qquad\qquad [2]$$

where W_λ is the intensity of radiation of wavelength λ emitted (W/m^3/mμ), c is the speed of light (2.99793×10^8m/sec), e is the Naperian or natural base of logarithms, k is Boltzman's constant (1.3804×10^{-23}J/$^\circ$K), and T is the absolute temperature ($^\circ$K).

Planck's Law applies only to black bodies, i.e., bodies which absorb all of the radiation incident upon them and emit the maximum possible amount of radiation at any given temperature. Such ideal

bodies do not actually exist in nature but may be approximated in the laboratory by constructing a cavity inside a body and measuring the radiation emitted from a small hole in the surface (Ref. 3).

All real bodies emit radiation which is some fraction of that given by Planck's radiation law. In order to account for this, a quantity known as the emissivity is defined and used as a multiplication factor on the right hand side of Eqn. [2]. The emissivity is the ratio of the amount of spectral radiation emitted by a real body at temperature T to the amount emitted by a black body at the same temperature. Hence the emissivity is always a positive fraction less than one and is equal to one only for a black body. One may speak of a "total" emissivity--the fraction of total energy emitted at a given temperature--or a "spectral" emissivity--the fraction of energy emitted at a particular wavelength (and, of course, temperature). The total emissivity of a body might be quite low while the spectral emissivity for certain wavelengths may approach unity. Both types of emissivity may vary with temperature, physical state, surface finish, molecular surface layers, etc. The emissivity cannot be calculated from any basic physical model but must be determined experimentally for each body (and often for different points on the surface of the same body). It is strictly a surface characteristic for opaque materials. The emissivity ranges from zero for "mirror-like" surfaces to nearly one for lamp black, zapon black, and such surfaces (Ref. 3).

Because of the variations in the emissivity of a surface, the determination of an absolute value of temperature by measurement of the intensity of emitted infrared radiation is fraught with difficulties.

It is possible, for example, that a particular surface will have a sufficiently large reflection coefficient that the body heat emitted by an experimenter might reflect off the surface of the examined object and be interpreted as a high temperature for that object. One can reduce difficulties such as this, or surface variations of emissivity, when studying composite materials by painting the surface to be studied with a uniform coating of lamp black, for example. While the difficulty involved with determining an absolute temperature value will still be present, this uniform surface coating will allow one to have some confidence that the temperature gradients observed on the surface are a result of material temperature differences and not spurious reflections from hotter objects in the surrounding environment.

Returning to the statement of Planck's Law, Eqn. [2], we might point out several other important physical characteristics of infrared radiation. Figure 2 presents a schematic representation of a family of spectral radiance curves for radiation from a black body at several different absolute temperatures. Such curves were determined experimentally long before Planck's mathematical law was found to quantitatively predict their form so closely. One first notes that black body radiation is a smooth, continuous function of wavelength with a single maximum occurring at one value of wavelength. This observation led to the statement by Wien of his displacement law:

$$\lambda_m = \frac{b}{T} \qquad [3]$$

That is, the wavelength, in microns, at which the maximum intensity of radiation is emitted is inversely proportional to the absolute temperature,

°K. The constant of proportionality, b, is known as the Wien displacement constant and has a value of 2897 μ/°K. Physically, the Wien Law states that the higher the temperature, the more the peak of radiation shifts towards shorter wavelengths and hence higher frequency and higher energy content (Eqn. [1]). The progression towards smaller wavelengths for increasing temperature is a phenomenon which most people have seen at one time or another. At moderate temperatures, the spectral emission peak is at wavelengths in the infrared and invisible to the human eye. As the temperature increases, the object will gradually take on a reddish hue, i.e., the wavelengths shorten to cover the red spectrum. At higher temperatures, the red brightens, changes into orange, yellow, and finally white when the emission spectrum extends to cover the green and blue bands. Perhaps the status of the earliest practitioners of thermography must be given to blacksmiths who quite early learned to gauge the proper tempering and heat treating temperatures of steel by judging the color to which they were heated.

A second important observation which can be made from Fig. 2 is that there is a single emission curve for each temperature of the black body. Furthermore, no emission curve ever intersects another. In particular, each curve lies above all other curves corresponding to lower temperatures of the black body. This fact means that if proper techniques are developed for measuring the spectral emission curves, one can uniquely determine the absolute temperature of a black body. Recall, however, that because of emissivity variations for real emitting bodies, this absolute temperature determination offers many difficulties to the experimenter.

Two other considerations are of some importance to understanding noncontact thermographic NDE methods: the system geometric relationships and the fidelity of surface thermal patterns to subsurface flaws. For an infrared system viewing any source, the received power at the system aperature is given by (Ref. 3)

$$H = \frac{W_\lambda \omega}{\Omega} \qquad [4]$$

where W_λ is the spectral emittance, ω is the angular field of view of the viewing system (defined by the optical system and the detector) and Ω is the total solid angle about the source. Thus, it can be seen that the primary geometric parameter which governs the response of the infrared viewing system is the relationship between the angle subtended by the source compared to the angular field of view of the system. If the source is small compared with the field of view of the detector (a point source), the received radiation will vary with distance between the source and detector but not with angle about the source. Interestingly, if the source is large compared with the field of view, the received radiation varies with neither distance to the source nor angle about it. This latter fact is a result of Lambert's cosine law which states that the radiant energy emanating in a given direction from any point on a surface is a function of the cosine of the angle between the normal to the surface at that point and the given direction. More specifically, the maximum radiation occurs along the normal direction to the surface and none tangentially to it.

The significance of Lambert's Law for infrared detection is that a detector viewing an emitting surface will always receive the same amount

of energy no matter the angle between the detector's line of sight and the normal to the radiating surface. This statement is true for both planar and general, curved surfaces, although it is easier to see and understand for planar ones. As the angle between the line of sight and the surface normal increases, so does the area of the surface viewed by the detector. The increase in viewed area exactly matches the reduction in radiation as given by Lambert's cosine law. Hence the total energy incident on the detector is constant. This, of course, is valid only as long as the emitting surface completely fills the detector's field of view. A simple rule in utilizing a detector system then is to make the source the only object in the field of view by appropriately controlling the field stop of the viewing system.

The second consideration mentioned previously that one must be aware of when using noncontact thermography as an NDE technique is the fidelity of the observed surface thermal patterns to the interior inhomogeneities or flaws. The relationship between the surface isotherms and the interior thermal patterns is, of course, governed by the thermal conductivity of the material and the distance between the surface and an interior region of interest. For very thin materials such as composite laminates, it has been shown that the fidelity of surface thermal patterns to interior flaws is quite good (Ref. 4). For bulk materials, thermography may be useful for qualitative indications of the presence of flaws but will not be nearly as good as other NDE methods for resolution of the flaw size and shape. For example, what might seem to be a rather sharp discontinuity may prove to have a weak thermal signature because of heat conduction through the material (Ref. 2).

The thermal signature can be improved by making the cooling rate at the surface as large as possible. This might be done by making the surface as nonreflective as possible and by augmenting radiant cooling by forced air circulation over the test surface.

There are two basic types of infrared detectors: (i) photon-effect devices and (ii) thermal devices. The photon-effect devices are sensitive to the wavelength of the received radiation while thermal devices respond only to the degree of heating caused by the incident radiation and are largely independent of wavelength. The performance of real-time thermography, such as with a video-thermographic system, requires that the entire field of view be scanned very rapidly so that the temperature of each field point can be measured and displayed many times each second. Such systems require the high sensitivity and very rapid response time of photon-effect devices.

Photon-effect devices utilize solid state materials which produce voltage, current, or resistance changes when irradiated by photons. These semiconductor materials are generally classified as photoemissive, photo-conductive, or photovoltaic detectors. Photoemissive detectors, originally discovered by Hertz, are materials which emit electrons when irradiated by photons having wavelengths smaller than a critical value which depends upon the material. (Another way of looking at this, of course, is that the energy or frequency of the photon must exceed a respective critical value.) Photoemissive devices are primarily responsive through the visible wavelengths down to approximately one micron. Hence, such devices are not used extensively in infrared systems. Photoconductive devices are semiconductors whose conductivity

changes when irradiated by photons. Photons of sufficient energy will cause bound electrons to jump into the conduction band and hence to become available as charge carriers. The response time of photoconductor materials is very fast with times shorter than one microsecond having been reported. Photo-voltaic cells are composed of p-n junction semiconductor materials. These cells produce a voltage when irradiated by photons. These devices also are characterized by a rapid response time. For maximum sensitivity, and to reduce extraneous thermal noise, it is usually necessary to cool the semiconductor material to low temperatures. Many commercially available thermographic detector systems require that liquid nitrogen be used for this purpose.

The rapid understanding and development of semiconductor materials after World War II also led to major changes in the detection of infrared radiation. The types of detectors discussed in the preceding paragraph have been incorporated into various commercially available infrared detection and viewing systems. One can obtain systems which scan the test surface in real-time as rapidly as 28 complete frames per second. The signal is conditioned and displayed upon television monitors in either gray scale or color format. The gray scale display units display continuous temperature readings using various shades of gray between black and white. The color display units select a series of distinct colors (as many as ten) to display those regions of temperature which differ from one another by a temperature band equivalent to the total temperature range divided by the number of colors available ($\Delta T = 1/10$th the temperature range for displays having ten colors). With these devices, one can monitor simply and rapidly the temperature gradient

profiles on the surface of the test objects for total temperature ranges between 1 and 1,000°C. Specific information and details on particular thermographic systems can be obtained from the manufacturers.

Application of Thermographic Nondestructive Testing
Procedures:

The sections which follow will deal with the application of thermographic testing. The information will be divided into the following sections: Procedures, Equipment, Parameter Selection, and Applications.

For the purpose of our present discussion, it will be assumed that all application procedures incorporate a thermographic detector of some type, such as a video-thermographic camera or other similar device. This part of the apparatus will be referred to simply as the "detector," and assume that the heat pattern displayed or recorded by that device is interpreted by the user in a fashion which suits his particular engineering or scientific purposes. Hence, we will be concerned in this section primarily with the production of heat patterns which display suitable detail for nondestructive testing or evaluation purposes.

A schematic diagram of a basic thermographic nondestructive testing and evaluation testing system appears in Fig. 3. Regardless of how the system is used, the basic principles of operation remain essentially unchanged. Discontinuities in material properties or material geometry in the specimen under examination are revealed by corresponding discontinuities in the heat emission pattern, which is produced by using the specimen as an emitter of energy that is introduced into the specimen by an external mechanical or thermal excitation.

The heat emission pattern so produced is detected by an infrared or thermographic camera (or other suitable device) and transmitted to the final system component which may display, record, and possibly interpret the heat pattern. Generally speaking, the detector and the display-recorder-interpreter are fixed for a given investigator since those components generally represent significant capital investments and sometimes require detailed integration and interfacing with other parts of the total engineering or investigative system.

On the other hand, the manner in which the heat emission pattern is produced frequently changes from specimen to specimen and from circumstance to circumstance. The choice of a specific method will generally depend on the type of flaw or defect to be detected, the material properties and geometry, the excitation devices which are available, and the nature of the thermographic detector that is available.

One of the basic choices to be made is whether the specimen is to be used as an active or passive heat emitter. While it is possible for the specimen to produce heat emission patterns by both processes simultaneously, the heat patterns emitted by most excitation devices usually fall almost completely into one of these two categories. As the terminology implies, passive heat emission occurs when the specimen is used simply as a conductor or conduit for energy transmission. The details of a heat pattern produced in that way are created by spatial discontinuities in that transmission process. Hence, for the most part, the detection of defects or flaws using this method depends on the degree to which the conductivity of the specimen is disturbed in local regions around those details to be revealed. Obviously, then, larger flaws

which disturb the conductivity over larger areas are easier to find than smaller ones. However, the location of the flaw relative to an observable surface, the projected area of a flaw relative to the direction of principle heat flow, the conductivity of the material in the flaw (if it is not a void), and a number of other factors to be mentioned in the Parameter Selection section also affect the detectability of a defect using this method.

There are two commonly used schemes for introducing heat into a specimen which is to be examined by passive thermography. The first of these schemes is the introduction of heat into the specimen by conductivity, i.e., by placing a heat source in direct contact with the specimen at some point so that the specimen conducts heat away from the source, or by placing a heat sink in contact with a specimen at some point so that heat is conducted by the specimen to the sink. Of course, both a heat source and a heat sink can be used together at two different points to establish a fixed temperature gradient across which heat is conducted by the specimen. Figure 4 shows two arrangements whereby heat is introduced into the specimen by conductivity. In Fig. 4a the heat source and heat sink are arranged at either end of a specimen which has a small defect at the position indicated. In Fig. 4b, the heat source is in contact with the entire longitudinal dimension of the specimen and the other longitudinal surface is free to dissipate heat by convection. Generally speaking, the arrangement shown in Fig. 4b is likely to produce a more distinct image of the defect in the heat emission pattern observed by a detector which views the free longitudinal surface in both cases, if similar amounts of heat flow are involved in the two instances.

In a simple sense, the defect represents a greater disturbance in the heat flow when the direction of flow is through the thickness of the plate than it does for the situation where the direction of the flow is along the longitudinal axis.

It is also possible to introduce heat into the specimen by radiation and convection. A flow of hot air or fluid can be directed at the surface of the specimen, for example. Two common arrangements are schematically depicted in Fig. 5. The common tendency is to direct the heat source at the surface opposite to the one viewed by the detector, as shown in Fig. 5a. However, it is also possible that an arrangement whereby the source of heat and the detector are on the same side of the specimen may be preferable. While it is true that it is certainly easier to transfer energy into a specimen by conductivity than by radiation or convection, the latter transfer scheme does have a number of advantages. One of those advantages is simplicity of operation since it is somewhat simpler to obtain or construct a source of hot air (such as a common heat gun) or hot fluid than to build a suitable device to transfer heat into a specimen by conduction, especially if the specimen has an irregular shape or imperfect surface. In fact, it is generally easier to obtain a uniform or reproducible regular pattern of heat using radiative or conductive energy transfer into a specimen or component, a distinct advantage of such schemes.

Another basic matter of importance for passive thermography procedures is the question of whether steady-state or transient conditions should be used to develop the heat emission patterns. For a steady-state experiment, the heat source, the specimen, and all of the heat

loss mechanisms are given sufficient time to reach thermal equilibrium before the thermographic data is recorded. Once the steady-state has been reached, the temperature distributions remain constant as a function of time. Such a procedure has the advantage of being more easily reproduced and more amenable to quantitative interpretations and comparisons. Once the entire system has reached thermal equilibrium, the number of operational or system-dependent variables that enter into the interpretation of the data that are recorded is minimized. Hence, the interpretation of the data is greatly facilitated. Also, it happens that the mathematical analysis necessary to represent a steady-state heat transfer problem is generally simpler and more easily applied to practical problems than the analysis which must be used for transient heat transfer situations. On the other hand, transient heating schemes have their advantages, too. One of the most obvious advantages is brought to mind by realizing that the largest temperature differences in a specimen occur at the first instant that a heat source is applied to the specimen. Following that first point in time, energy is transferred according to Fourier's Law and distributed in such a way so as to balance the energy input against conduction, convection, and radiation losses. The temperature gradients are reduced by this process until thermal equilibrium (a steady-state condition) is reached. While a defect or flaw represents the same obstacle to the transfer of heat during the transient as well as during the steady-state situation, the thermographic detector depends on temperature differences for the resolution of data, and these temperature differences must be detected by the observation of a free surface. Hence, in some instances, transient

heating schemes may reveal defects and other discontinuities that are not easily detected by steady-state methods. Some examples will be cited in the section on Applications.

The development of heat emission patterns by passive methods depends almost entirely on heat transfer characteristics for its resolution capabilities. To use the common electrical analogy between Fourier's and Ohm's Law, the temperature difference details which reveal defects and flaws of interest are proportional to the conductive heat flow times the summation of thermal resistances in the region of the flaw. Hence, the effect of the flaw or defect can be thought of as a local variation in the thermal resistance which then is reflected in an observable temperature difference in that locality. In other words, the flaw acts like a local variation in the material property of conductivity for such passive measurements. Of course, in the engineering sense, the flaw is also a very important mechanical disturbance. That fact can be used to develop thermographic details when "active" heat generation procedures are used. Three examples of such active procedures are indicated by the schematic diagrams in Fig. 6.

Figure 6a depicts the situation in which energy is generated by hysteresis when a specimen is deformed mechanically. It is a well known fact that when most materials are cyclically deformed, even in the elastic range, some of the mechanical energy is dissipated by non-conservative micro-mechanical deformation processes such as dislocation motion, impurity diffusion, and other complex local molecular or atomic activity. For polymeric materials, these processes bring about what is commonly called viscoelastic response. The amount of energy dissipated

by such mechanisms may range from imperceptible amounts up to several percent of the input energy. Unfortunately, most of the attention that has been given to hysteresis has centered on crystalline solids and has been concerned almost entirely with a part of the field called "anelasticity," which is commonly concerned with atomic diffusion events that are activated by stress including such things as grain boundary motion, single or paired solution atom motion, and twin boundary activity. While these events may be prominent in the small strain range, the heat produced by them is not significant because of the low ratios of dissipated-to-input energy, a low level of input energy for small strains, and the low frequencies of oscillation at which these events are commonly excited. For composite materials with polymeric matrices, viscoelastic dissipative hysteresis dominates the heat generation, but hysteresis energy heat patterns can be generated in metal matrix composites as well.

Two parameters are especially important in the generation of such heat patterns using mechanical excitation, as is indicated in Fig. 6a. The first of these is the stress or strain level at which the specimen is deformed. Depending upon the material used, the deformation process, the type of defect, and other variables, a stress or strain level greater than or equal to roughly one-third of the level required to fail the specimen is sufficient to produce observable heat patterns around defects of engineering interest in most cases. The second major parameter of importance is the cyclic frequency with which the mechanical load is applied. If other things are equal, the amount of power introduced into the specimen is directly proportional to the frequency of

oscillation, so that the best frequency is the highest frequency available since temperature differences in the region of a defect will be proportional to the differential amount of energy generated by the defected and adjacent undefected regions. It should be mentioned, however, that energy dissipation mechanisms may be frequency and temperature dependent so that the optimum frequency may not be the largest one easily obtainable with the test rig available. Trial and error is called for. Most heat patterns that are generated in composite materials using this active hysteresis energy emission scheme are created by cyclic frequencies between about five and thirty Hz. One of the advantages of the mechanical excitation scheme is the fact that the dissipation of the defect or defected region is in direct proportion to its mechanical importance, or in another sense, to its mechanical disturbance of the material response in that region. Hence, an element of interpretation is added to the information obtained in this way. It should also be mentioned that while this procedure can be used nonde-structively, it is also possible to watch the growth and development of defects by simply observing the cyclic application of load levels and load histories which are sufficient to cause such growth. In that way, the chronology of damage development can be followed.

Figure 6b shows another example of an active heat generation procedure. If proper frequencies of mechanical excitation are chosen, resonant body vibrations of the specimen or component can be excited. Energy is dissipated, and a heat emission pattern is formed, in pro-portion to the stress distributions which are created by the resonance vibration mode. Defects and flaws, or damaged regions, are revealed not

only by the manner in which they disturb the generation of the heat pattern, but also by the manner in which they disturb the vibration mode shape as revealed by the heat pattern.

Figure 6c indicates yet another method of mechanical excitation which has been dubbed "vibrothermography" by the authors. That procedure involves the introduction of high frequency ultrasonic excitation into a specimen by affixing an ultrasonic transducer or shaker to the specimen at some point or points. The frequency of excitation is varied in such a way that local flawed regions are set into local resonance. In addition to the hysteresis energy dissipation in the region of local vibration, another very strong source of energy dissipation frequently develops due to the interaction of internal flaw surfaces when they interact with one another during local vibration motions. For example, in some cases it has been determined that the surfaces of a delamination rub together to produce a very strong dissipation source during this type of excitation. Vibrothermography has the advantageous capability of being able to selectively resolve different defects by the use of different frequencies of excitation, and the procedure has shown exceptional sensitivity to defects which have internal free surfaces which are in close proximity to one another.

While the commonly used procedures for thermographic detection of defects are outlined above, an enormous number of variations have been used and others are being developed. In fact, one of the most desirable aspects of thermography is the flexibility with which it can be applied to a variety of engineering situations. The reader and user is well advised to use his imagination and try his hand at the development of

suitable procedures which may be based on the details mentioned above or on other innovative ideas.

Equipment:

The thermographic detector is the heart of every thermographic unit. Systems commonly in use for nondestructive evaluation range from infrared film in standard cameras to thermal imaging video devices. Generally speaking, the video devices which are available at this writing appear to be best suited to the nondestructive evaluation purposes under discussion. One of the most frequently used such systems is the Thermovision system manufactured by the AGA Corporation. That system is a photon device which divides incoming images into a linear string of picture parts by using two opposed-axis rotating mirrors to split up the incident image. The picture parts fall on a thallium activated indium antiminide crystal (which is cooled by liquid nitrogen) and affect its photovoltaic properties. The resulting electrical signals are used to construct a video signal string which is then displayed on a standard CRT, and may also be displayed on a ten-color-isotherm monitor. It is also possible to record and to process the image in various ways. Such a system has a temperature sensitivity of about .1°C, and has the advantage of being time-resolved to about one-twentieth of a second. The operation of such a system is relatively simple since it is quite similar to a closed circuit television arrangement. Unfortunately, such systems are also rather expensive with costs commonly running to the $40,000 range as of this writing.

The rest of the equipment required for a thermographic system is relatively simple and easily obtained. Referring to Fig. 3, the

mechanical or thermal energy source, depending upon the type of excitation to be used as discussed in the previous section, can be a mechanical testing machine, a dynamic shaker or shaker table, an ultrasonic transducer and power generating system, or any one of a variety of conductive or radiative heat sources. Some or all of this equipment is commonly available in a research laboratory.

If the equipment (or money to purchase it) is available, it is a great luxury to have equipment which can assist in the recording and interpretation of the images obtained by the thermographic detector. Image analysis has become a very sophisticated science and art. Digital recording, analysis, enhancement, and interpretation schemes are available from a variety of sources. Although the complexity of this field is somewhat forbidding, it has a great deal to contribute to the use of thermography for nondestructive evaluation and testing purposes.

Parameter Selection:

There are a number of parameters which influence the capability of thermographic methods to detect flaws in materials. One of the most important of these is the conductivity of the materials to be observed. While the density and specific heat of various engineering materials rarely changes by an order of magnitude, the thermal conductivity may change by four or more orders of magnitude. Hence, thermal conductivity has a dominant influence on this material interrogation scheme in many cases. It is certainly obvious that, since the image of defects to be detected is formed by temperature differences from point to point, materials which have a very high thermal conductivity are difficult to

examine with thermographic techniques since temperature differences are minimized by the high rate of heat energy transfer from point to point. There is a secondary consideration, however, which "works the other way." Thermographic detectors depend upon observations of a surface, so that any thermal information from the interior must be transmitted to the surface by conductivity. If the thermal conductivity of a material under observation is extremely low, it is possible to mask or hide thermal detail that is developed in the interior of the specimen. However, these two restrictions generally have the influence of requiring selections of different techniques and different information to be obtained rather than prohibiting the use of thermography. As we will see in the next section, thermography has been successfully applied to the detection of defects in materials as widely different in thermal properties as common metals and polymers.

A demonstration of the essence of this effect appears in Fig. 7 taken from Ref. 5. It is assumed that differential heating (and therefore a thermal image) is generated over a distance given by the dimension specified in the abscissa, caused by a mechanical excitation with a frequency specified by the ordinate. The curves represent the combinations of frequency of excitation and dimension of detail which just correspond to "thermal resonance," i.e., the frequency at which thermal information can just be transmitted over the distance given by the abscissa. The ordinate, which is a logarithmic scale, clearly shows the strong dependence on material thermal conductivity.

Another consequence of thermal conductivity differences is shown in Fig. 8, also taken from Ref. 5. That figure shows the apparent size of

a thermal image (normalized by the actual size of the heat source) as a function of the sensitivity of the detector in units of percent of the thermal source strength over a distance of .1 of the ordinate value. For example, as shown on the figure, if the instrument used to observe a heat pattern can resolve one percent of the source strength, then the apparent size of the pattern will be about 5 or 6 times the dimensions of the actual source provided the spatial resolution of the camera is not less than that apparent size. In fact, for many practical situations, this apparent size of 5 times the source size is a useful rule of thumb. The figure is also helpful in the interpretation of information from a heat image. For specific situations it is well to solve the heat transfer problem using the classical approaches discussed widely in the literature. It should be mentioned that heat transfer problems in composite materials, especially layered composite materials, are not as straight forward as those in homogeneous isotropic materials. Discussions of such problems can be found in References 5 through 8.

Surface reflectivity and emissivity are also parameters of importance as discussed previously. The reflection of radiant energy from the surface of a specimen under observation may interfere greatly with attempts to observe and record the heat emission pattern being developed by the specimen. For the thermal radiation band in the electromagnetic spectrum (defined as the portion of the spectrum between wavelengths of about 1×10^{-7} m and 1×10^{-4} m) reflectivity is influenced not only by the material properties but also by the surface condition. Hence, it is very difficult to classify different surfaces and corresponding quantitative reflectivities. It is best to determine by experiment in one's

own laboratory the degree to which reflectivity will interfere with the observation of thermal data. The radiant energy from a lightbulb, a human body, or other heat source will generate glaring reflections off of polished aluminum, for example, while a number of other surfaces, especially those painted with so-called "flat" paints, show very little reflectivity (Ref. 9).

The emissivity of the surface is a measure of its ability to emit radiant thermal energy per unit time and unit area, usually normalized by the emissivity of an ideal "black body" as defined in common physics texts. To that extent, for our purposes, the emissivity represents the ability of a surface to transmit the thermal information of interest that is developed in the interior of a body. Emissivity generally depends upon the material or substance, the surface condition (including roughness), and the temperature. Values of emissivity are widely tabulated and quoted (c.f. Ref. 10).

One other parameter is sufficiently general so as to require discussion. That parameter is the damping characteristics of materials, especially fiber reinforced composite materials. When mechanical excitation is used to develop heat images, the ability of a material to develop such images is completely controlled by its hysteresis characteristics, commonly known as damping. The damping or damping ratio of materials is difficult to measure and may depend upon temperature and frequency. The damping and dynamic mechanical behavior of fiber-reinforced composites has been discussed in a review article by Gibson (Ref. 11) and in another excellent discussion of experimental techniques in an article by Gibson and Plunkett (Ref. 12). A discussion of heat

emission of composite materials under mechanical fatigue loading is also provided in Ref. 13. In general, as one might expect, materials which have complicated microstructures, and especially those which have viscoelastic behavior, usually dissipate energy efficiently and develop strong heat images. Since many of these materials are also relatively poor conductors, they are ideal for the application of thermography as a nondestructive evaluation scheme.

Applications:

The principle application of thermography for nondestructive testing and evaluation purposes appears to be for the detection of defects and flaws and the general monitoring of damage development and growth. In 1969 Schultz and Tsai (Ref. 14) discussed the damping of composite materials and indicated that the energy loss due to damping was dependent upon the frequency of oscillation and the orientation of the orthotropic materials relative to the axis of mechanical excitation. In a subsequent report Segol and Tauchert (Ref. 15) measured the heat generated during the torsional excitation of glass-fiber reinforced plastic specimens at frequencies of 120, 210, and 300 cycles per minute. They found large temperature increases and observed discoloration and delamination in the glass-epoxy composite materials with a consequent reduction in properties.

The use of thermography to detect flaws and defects, and to follow damage development, began in about 1974 (Ref. 16 and 17). It was found that thermography is especially useful to follow the complex development of damage in the vicinity of notches such as holes in composite lami-nates. Boron-aluminum and boron-epoxy materials were used in those early studies.

As techniques have been developed, methods to detect defects and damage development in unnotched composite laminates have been devised and considerable success has been reported (Ref. 19). It has also been determined that thermography is especially sensitive to certain specific types of damage in composite laminates. Perhaps the most obvious such conclusion in the literature is that thermography is especially sensitive to debonds and delaminations (Ref 20 and 21). This appears to be true when either mechanical excitation or convective-radiative incident heat is used (Ref. 22). In fact, resonant vibration (of the body vibration or local vibration type) has been found to be an especially sensitive method for the excitation of heat patterns generated by internal defects which have free surfaces such as debonds, delaminations, or cracks (Ref. 23). Mignogna and Green have also reported that resonant vibrations created by high-power ultrasound can also be used to detect the nature of internal boundaries (Ref. 24).

Since thermography works on the basis of optical field techniques, it can be applied to the quick observation of large surfaces. Because of that characteristic, it is especially suited to the quick scanning of engineering structures for the detection of defects and the identification of regions that should be examined more carefully. Also, if video thermographic equipment is used, the time resolution of the system permits the detection and recording of some of the dynamic aspects of damage development, and in some instances can be a major advantage in the sense that systems that are being dynamically tested or used for some engineering purpose do not have to be interrupted for observation.

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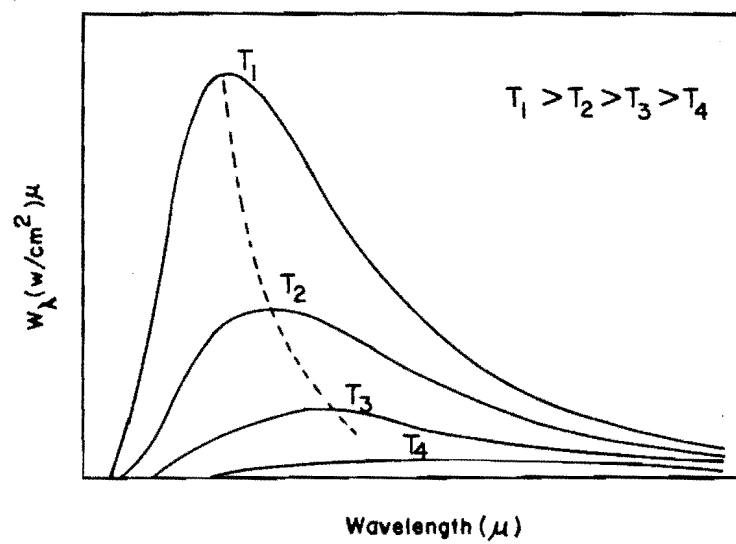
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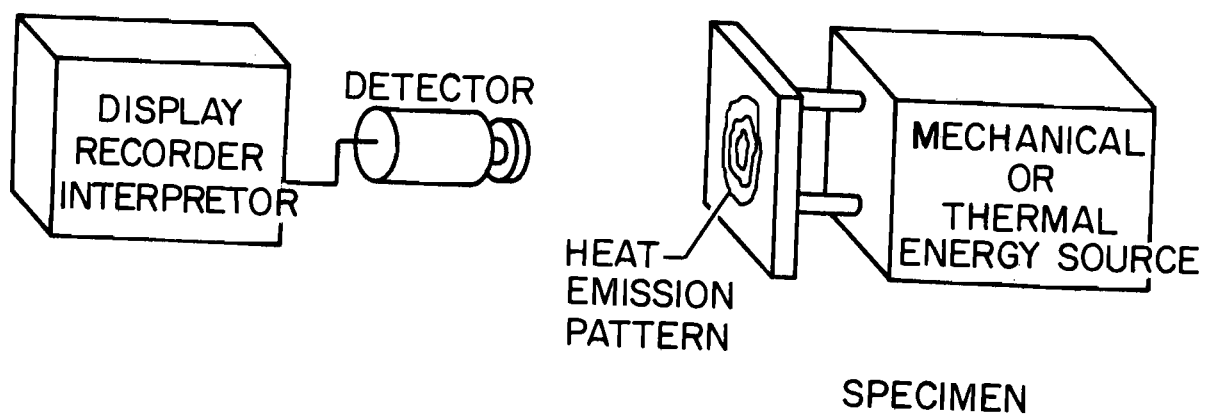
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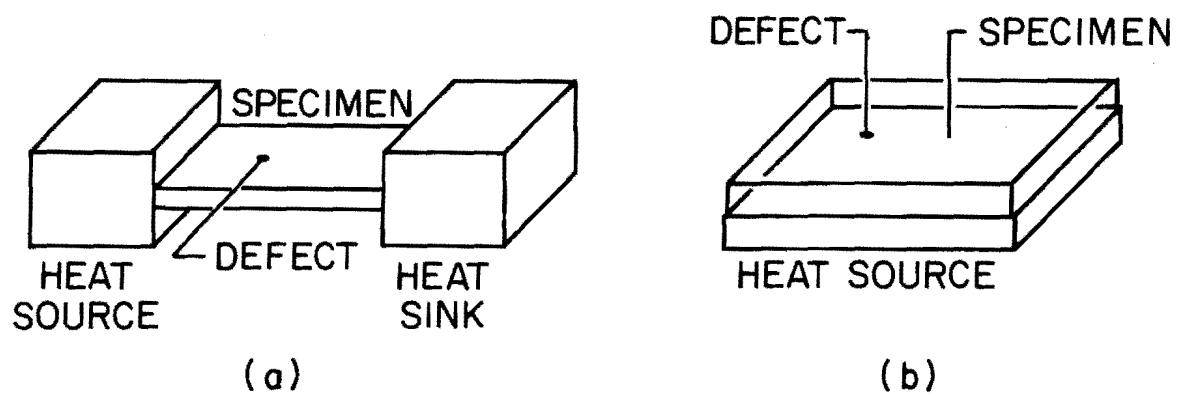
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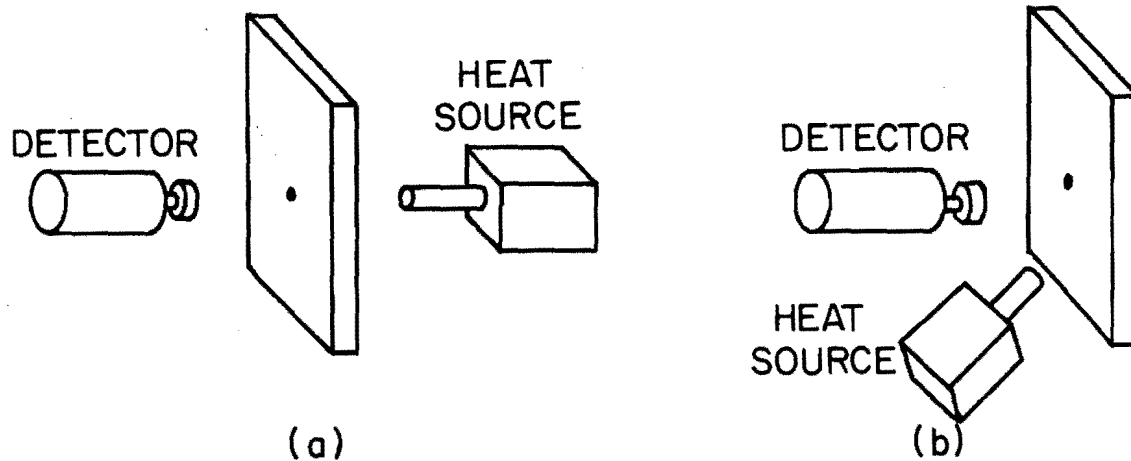
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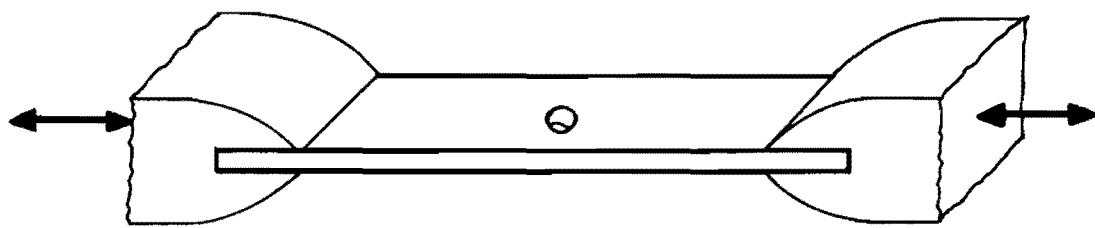
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(a)

Body Resonance

(b)

Ultrasonic
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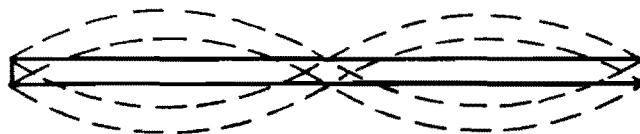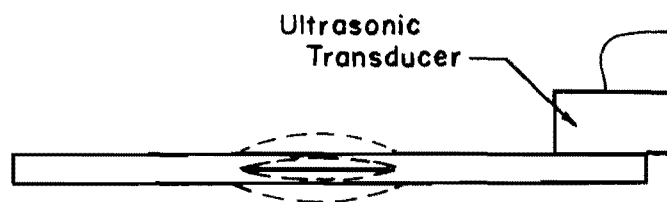
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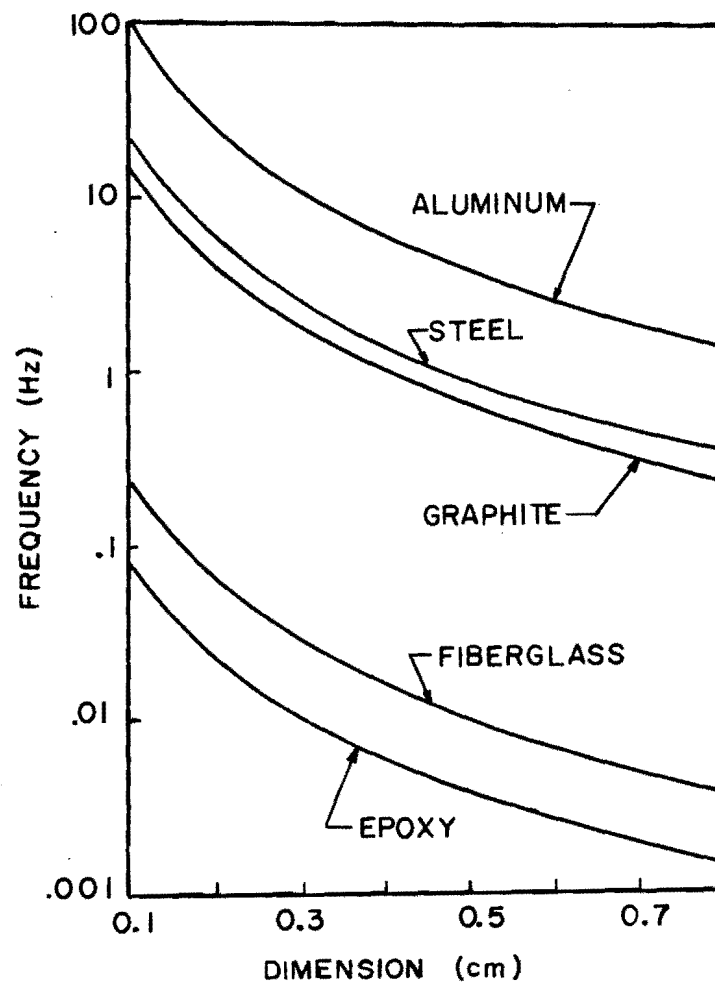
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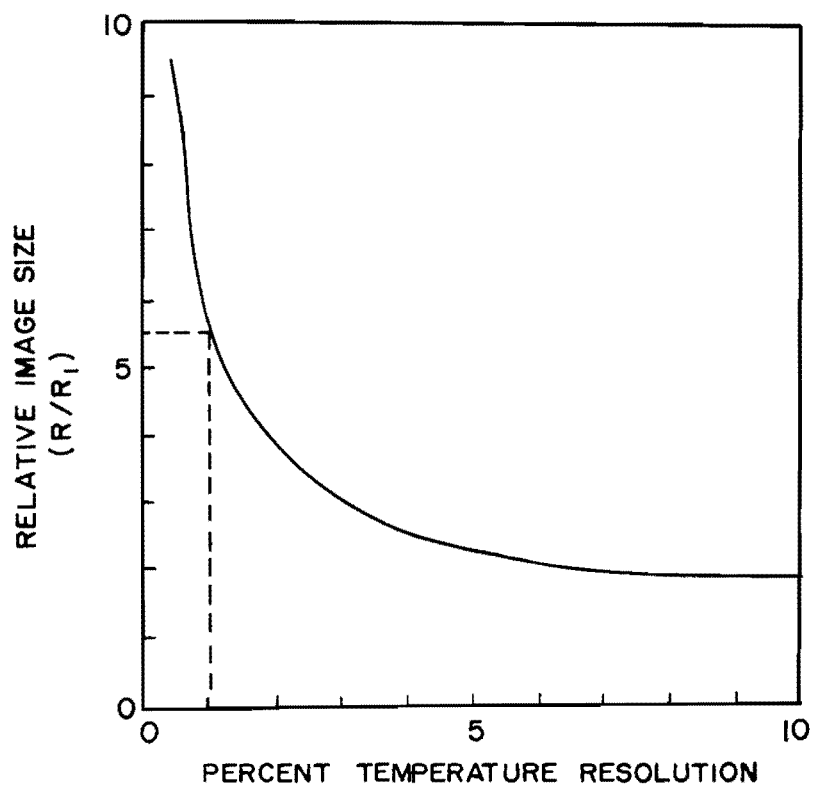
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GRAPHY--A STATE-OF-THE-ART REVIEW -
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